Optical design of the SIM System Testbed 3

Renaud Goullioud[1], Alireza Azizi[2]

Jet Propulsion Laboratory, California Institute of Technology,
4800 Oak Grove Drive, Pasadena, CA 91109

ABSTRACT

The SIM system testbed III is a full 3-baseline interferometer mounted on a full-scale flexible structure developed at the Jet Propulsion Laboratory under the Interferometry Technology Program. The goal of the testbed is to demonstrate angle and fringe tracking of a dim star by feed-forwarding the information from the two interferometers looking at bright guide stars. This paper presents the optical architecture of STB3 and the first results obtained with the three interferometers running.

The testbed consists in two separate systems isolated from the ground: the pseudo-star and the instrument it-self. The pseudo-star is a passive triple reverse interferometer on a rigid table. The originality of the pseudo-star design is the diffraction gratings used to split the stellar wavefront into 3 stars. They minimize the differential position jitter of each star from the others, reducing the overall error of the experiment. The instrument is a triple Michelson interferometer on a SIM-like structure. Each interferometer runs a CCD camera and two fast steering mirrors for angle tracking and, an internal metrology system, an Avalanche Photo-Diode and an active optical delay-line for fringes tracking. An external laser metrology sensor monitors the relative orientation of the baselines.

Keywords: interferometry, SIM, optics, pseudo-star

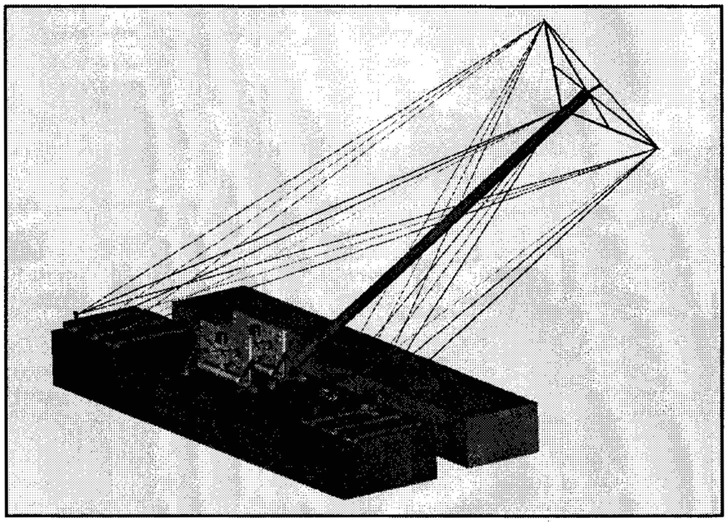
1. INTRODUCTION

The SIM system testbed III (STB3) is a full 3-baseline interferometer mounted on a full-scale flexible structure developed at the Jet Propulsion Laboratory under the Interferometry Technology Program. The goal of the testbed is to demonstrate dim-star angle and fringe tracking on a flexible structure by feed-forwarding the information from two "guide" interferometers. This paper presents the optical architecture of STB3 and the first results obtained with the 3 interferometers running. The electronics and the real-time control system [4] inherit from the RICST testbed [1].

The testbed consists in two separate systems isolated from the ground: the pseudo-star and the instrument it-self. Figures 1a shows a complete picture of the testbed including the metrology boom with all the external metrology beams. One can compare the STB3 test article with the SIM flight article on Figure 1b. Figure 2 shows both the instrument and the pseudo-star layout and all the starlight beams. However all metrologies beam are not displayed on the picture.

The pseudo-star is a passive triple reverse interferometer on a rigid table. The three artificial stars are located at 15 degrees from each other in the space. A white light source coupled with a Nd:YAG laser produces the simulated stellar wavefront. The originality of the design is the diffraction gratings used to split the stellar wavefront into 3 (or more) stars. They minimize the differential position jitter of each star from the others, reducing the overall error of the experiment. The science star is the white light star whereas the two others are laser stars.

[1] Send correspondence to: M/S 171-113 or 818 354 7908 or renaud@huey.jpl.nasa.gov
[2] Send correspondence to: M/S 171-113 or 818 354 0639 or azizi@huey.jpl.nasa.gov



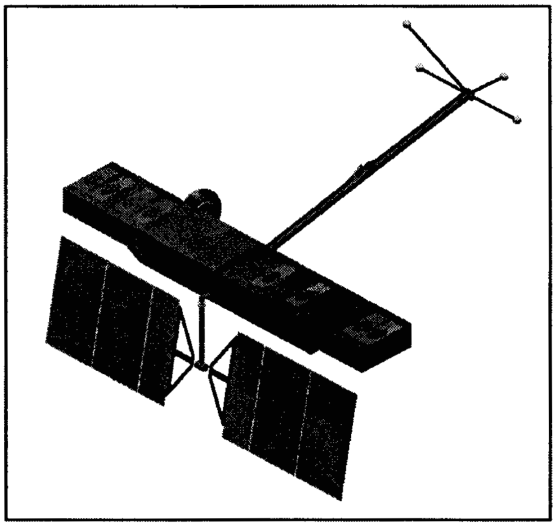


Figure 1a. & 1b. STB3 Testbed (left) and SIM flight article (right).

The instrument is a triple Michelson interferometer on a SIM-like structure. One interferometer is defined as the "Science" baseline whereas the two others ones are called "Guide" baselines. Each interferometer runs a CCD camera and two fast steering mirrors for angle tracking and an Avalanche Photo-Diode and an active optical delay-line for fringe tracking. An internal heterodyne laser metrology sensor monitors the instrument optical path and controls the position of the delay line.

In the first section we will describe the pseudo-star, especially the use of diffraction gratings to create the 3 artificial stars. Then in the second section we will explain the optical setup of the test article. The third section presents the various metrologies used to monitor the internal and the pseudo-star paths as well as the external metrology setup. Finally, section 4 will be a description of the simplified initial phase and the first results obtained.

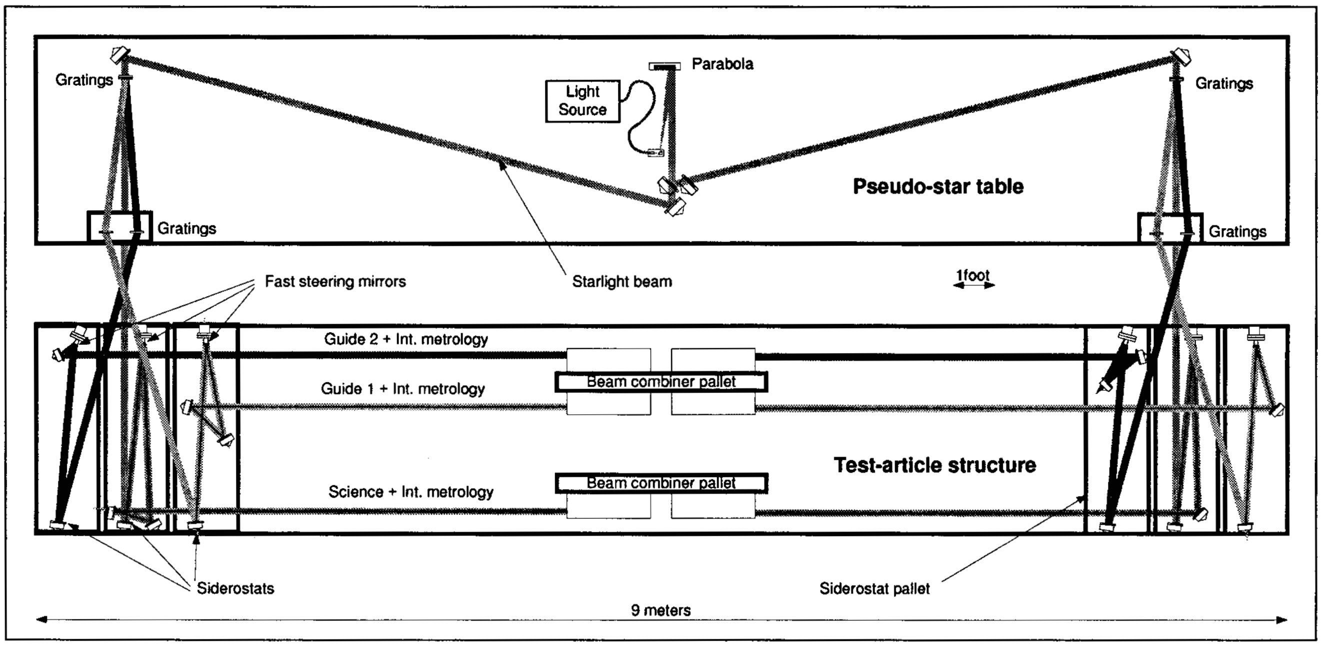


Figure 2. STB3 top view optical layout (the metrology boom is not represented).

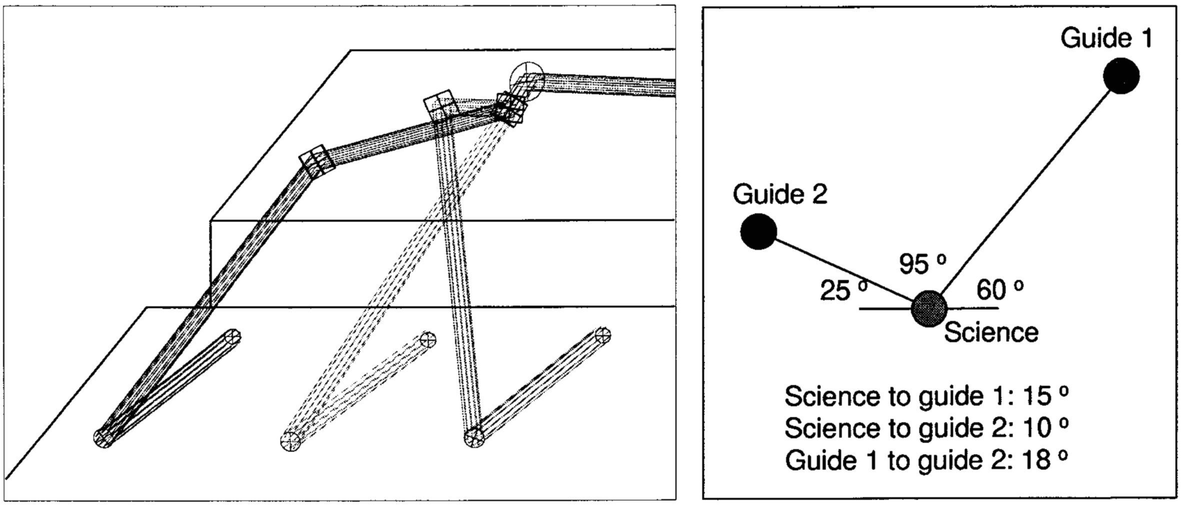


Figure 4a. & 4b. Grating location on the left arm of the pseudo-star (left picture). Apparent location of the three star in the "STB3 sky" (right picture).

2. Gratings

Each side of the pseudo-star is symmetrical in order to simulate a common wave front. A stack of two transmission diffraction gratings divides the incoming beam numerous beams. The light travels through both gratings creating various configurations of diffraction orders: zero-zero, zero-first, first-zero, first-first, zero-second, etc. However the blazing of the grating lines disperses most of the light into the zero order and the first positive order. The beam produces by both grating zero-order is not deviated. It will be used for the science star beam since it is insensitive to the wavelength. The zero-first order and first-zero order beams will be the two guide ones. Each guide star beam goes then to a second grating used to fold the beam toward the direction of the collectors on the test-article. Figure 4a and 4b shows the location of the gratings in one of the two arms of the pseudo-star. Table 1 lists the order distribution and the transmission of the gratings.

Table 1. Grating distribution

		Dividing grating pair		**Folding grating**		**Total**
		First	**Second**	**Left**	**Right**	
"Science" star beam	Diffraction	Zero order	Zero order			
	Transmission	71% @650nm	71% @650nm			50% @650nm
	Distortion	$\lambda/20$	$\lambda/20$			$\lambda/14$
"Guide 1" star beam	Diffraction	First order	Zero order	First order		
	Transmission	20% @532nm	50% @532nm	70% @532nm		7% @532nm
	Distortion	$\lambda/20$	$\lambda/20$	$\lambda/20$		$\lambda/12$
"Guide 2" star beam	Diffraction	Zero order	First order		First order	
	Transmission	50% @532nm	20% @532nm		70% @532nm	7% @532nm
	Distortion	$\lambda/20$	$\lambda/20$		$\lambda/20$	$\lambda/12$

The sensitivity analysis shows that common motion of the three stars is preferable to relative motion of one of the star. The grating based configuration provides a relatively small sensitivity to mechanical vibration compared to a beam-splitter/mirror based design. Table 2 presents the various tilt and shear sensitivities of the two kinds of gratings used. Indeed the horizontal shear mode and the clocking mode are the dominant ones. Using the Path-length feed forward equations one can establish the stability requirements: 10 nm rms.

2. PSEUDO-STAR

This section is a description of the triple pseudo-star developed for STB3. The pseudo-star creates 3 pairs of coherent collimated beams to feed the three baselines of the interferometer: two "guide" and one "science". The design of the pseudo-star is very critical, since it has to be more stable than the test article in order to succeed (20nm rms of piston jitter above 2 Hz). Finally the wave-front quality should be good enough (at least $\lambda/15$ rms) to obtain a good visibility of the interference fringes (V=0.9). The Pseudo-star is mounted on the top of a rigid 9 meter long honeycomb table.

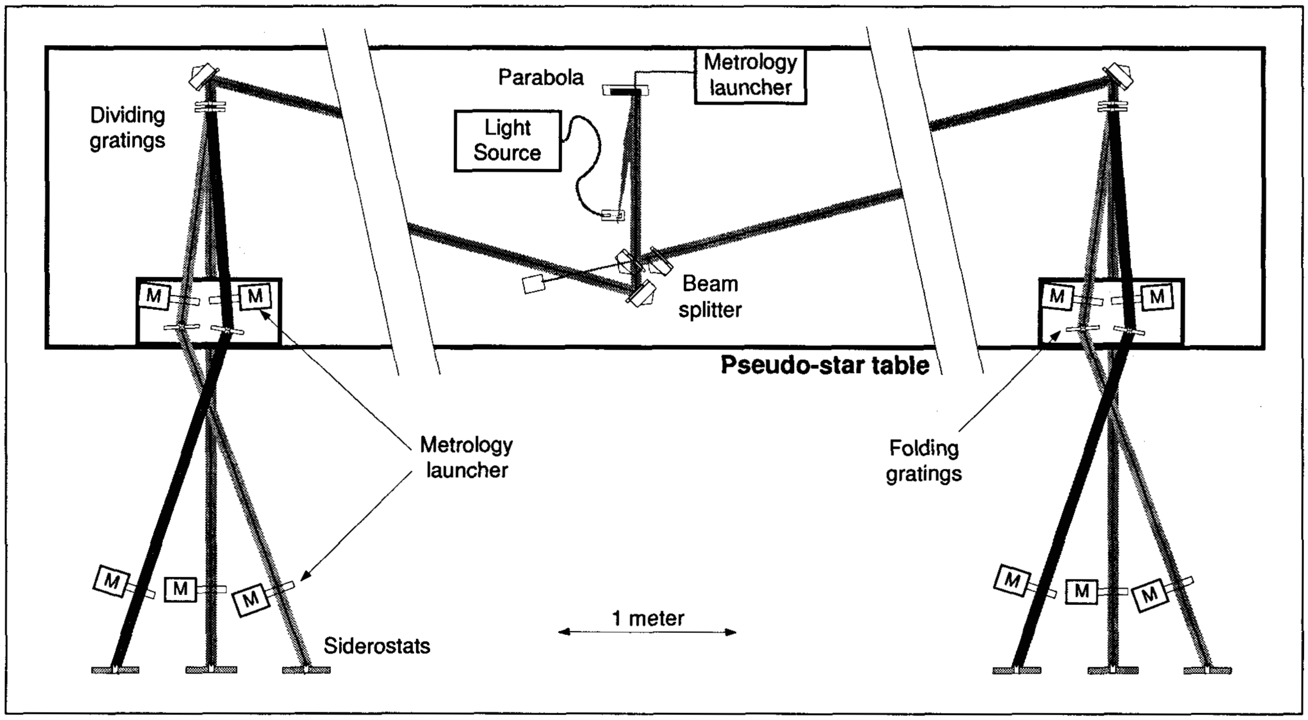


Figure 3. Pseudo-star optical layout.

The pseudo-star must produce wavefronts to feed the three pairs of collectors of the test article. Each collector of a pair must receive light from the same wavefront. Since it's impossible to create a unique 10 meter large flat wavefront in the lab, we produce two coherent copies of the same wavefront using a reverse interferometer (Michelson). The parallelism of the two pseudo-wavefronts must be very stable and well know. The starlight is issued from the same source but the wavefronts are fed to each baseline at various angles to simulate the separate stars. The three pairs wavefronts must be rigidly connected together to insure than the star are not moving in respect from each other. This is main error we have to fight.

1. Light sources

The "Science" star is a 3100K black body white source (550-800nm) whereas the "Guide" starlight is coming from a 532nm green Nd:YAG. A 550nm short wave pass filter is used as a dichroic filter to combine the light of both sources into a 5µm single mode optical fiber. The fiber output is at the focus of a parabolic mirror used to collimate the starlight beam. The light beam is 60mm in diameter in order to illuminate the 50mm siderostats and to tolerate small displacements of the test article. The starlight beam is then divided into two by a non-polarized broadband beam splitter. Each beam is routed toward each side of the pseudo-star table (cf. Figure 3).

Table 2. Mechanical sensitivity of the two gratings (for each "Guide" starlight beam). Numbers are ratio of starlight beam error over mechanical disturbance per grating. To be compared with a beam splitter + mirror design.

Direction	**Dividing grating**	**Folding grating**	**Beam splitter**	**Mirror**
Horizontal shear	270 nm/μm	440 nm/μm	0	0
Vertical shear	0	0	0	0
Piston	30 nm/μm	100 nm/μm	1400 nm/μm avg.	1400 nm/μm avg.
Horizontal tilt	40 μrad/mrad	10 μrad/mrad	2000 μrad/mrad	2000 μrad/mrad
Vertical tilt	0	0	2000 μrad/mrad	2000 μrad/mrad
Clocking	260 μrad/mrad	430 μrad/mrad	0	0

The sensitivity analysis shows that the relative location of the six pseudo stars must be known to better than 5 arc-seconds. Specific alignment procedures have been identified to be able to align the parallelism of the left star beams with the right star beams to better than 3 arc-seconds and to measure the location of the guide stars relative to the science star to better than 5 arc-seconds. These alignment techniques use 2 arc-second pentaprisms, 1 arc-second inclinometers and a 2 arc-second theodolite.

3. Pseudo-star Metrology

The pseudo star metrologies are used to monitor the behavior of the pseudo star. There are 11 pseudo star metrologies. Figure 3 shows all the pseudo-star metrologies.

Each metrology monitors a part of the pseudo star path between two corner cubes, except the first one. The first metrology is different because due to the architecture of the pseudo star, the metrology beam has to go through an unpolarized beam splitter. For this metrology the beam launcher is located behind the parabola, and the 2.5 mm metrology beam is launched through a 4.58 mm hole in the parabola. Since both polarizations go to both arms, and only one of the polarizations is needed from each arm, a 1/4 wave plate is attached to one of the corner cube, in the second arm a polarizer is attached to the corner cube. By adjusting the angle of the 1/4 wave plate (not at 45°) and the polarizer, the signal at the detector can be maximized. Note that due to 1/4 wave plate, the same polarization from both arms reach the detector, S, S or P, P.[9] The reason for this configuration rather than two polarizers was to increase the signal to noise ratio since the metrology beam has to pass through at least one grating. The main reason for the polarizer was to reduce the self-interference effect. The data from the pseudo star metrologies will be recorded and use in the post processing and analysis of interferometry data.

3. STARLIGHT SYSTEM

The section describes the test-article of STB3. It is composed of 3 interferometers with two siderostats, two fast steering mirrors, two delay lines, one beam combiner, one camera and one fringe detector (an avalanche photo-diode or a camera) in each baseline.

The test article is quasi full-scale copy of the SIM flight article. It is composed of the structure, the metrology boom and kite, the siderostat bay and the beam combiner assemblies. The structure is a flight-like honeycomb panel-based structure, 9 meter long, 1.5 meter wide and .75 meter thick. The metrology boom is 7 meter long, stretching from the center of the structure at 41.5°, holding a 2 meter large rectangular kite at its end. Four corner cubes are located at the corners of the metrology kite. The six siderostat bays are located on the top of the structure, three at each end of the test-article. The three beam combiner assemblies are located at the center on the structure. Figure 1a shows the test-article with the boom and the pallets.

4. Siderostats

The siderostat bay pallets are 1.5 x 0.45 meter honeycomb breadboard attached to the structure via kinematics mounts. Each six siderostat bays are identical. The light coming from the pseudo-star hits the siderostat mirror, then the light is routed to the Fast Steering mirror and one or two relay optics. The light is then sent into the direction of the beam combiners. A 12.7mm open face corner cube is located at the center of each siderostat mirror. The line between the vertexes of the two siderostat corner cubes defines the baseline of each interferometer. These six vertexes are aligned so that the three baselines are quasi-parallel. However, as the structure is flexible at the sub-micron level, we use the network of external metrology sensor to monitor the relative misalignment of these true baselines. Although all siderostats are motorized on SIM, only the two siderostats of the science baseline are motorized on STB3.

siderostat layout picture

5. Fast Steering Mirrors

The fast steering mirrors are two axis tilt actuators from Physik Instrumente. They are composed of a mirror mounted on a flexure with three PZT stacks located at 120 degrees from each other. The PZT actuate the tilt of the mirror. Strain gauges are mounted in parallel with the PZT; they monitor the expansion of the PZT stacks. An active loop in the PZT driver servos the PZT expansion with the stain gauges. One can provide up to 1200 μrad p-p of tilt motion with a resolution of 0.05μrad and less than 1nm of piston. The star tracking camera generates the FSM command signal.

6. Beam combiner assembly

The beam combiner pallets are 1.5 x 0.9 meter honeycomb breadboards, attached on their side to the structure using 3 points kinematics mountings. Figure 5 is an optical layout of the beam combiner described in this paragraph. Figure 6a shows one "guide" beam combiner. The light coming from the siderostat bays enters first the delay lines, then reflects onto a couple of folding mirror and then reaches the beam splitter used to recombine the light. The internal metrology launchers are located at the top of the beam combiner pallet. The metrology beams are injected into the starlight beams through 5mm holes at the center of the folding mirrors. The three beam combiners are the identical, except for the science beam combiner that has an extra feature: it produces dispersed fringes.

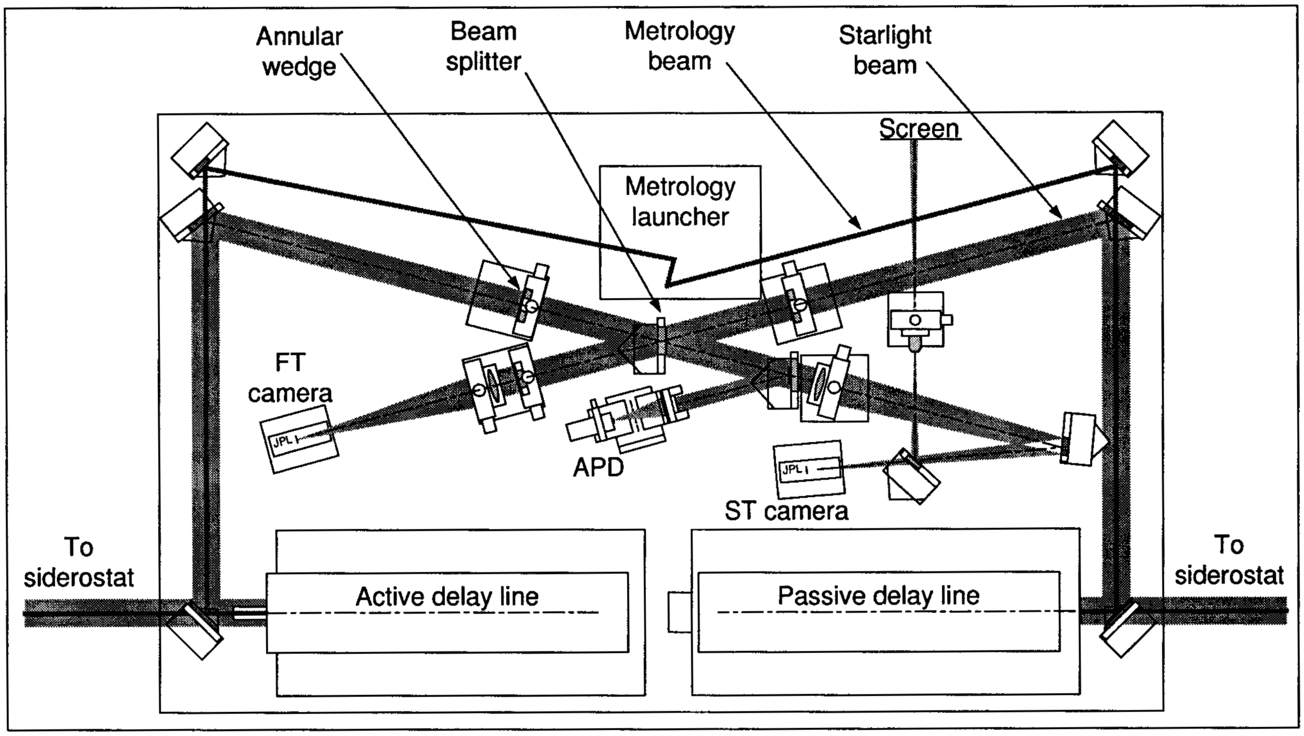


Figure 5. "Science" beam combiner layout (the Guide beam combiner layout is identical except for the FT camera that is replaced by the APD).

7. Optical Delay Line

We used the flight like optical delay lines developed by JPL for the interferometry missions (they are visible on the bottom of Figure 6) [2]. They are used to equalize the optical path between the two incoming starlight beams. The beam entering the delay line is focused on a flat secondary mirror by a parabolic mirror. The beam then leaves the delay line after reflected back to the parabola mirror from the flat mirror. Since only the relative optical path difference between the two beams is important, it is enough to only control one of the delay lines (the "active" delay line).

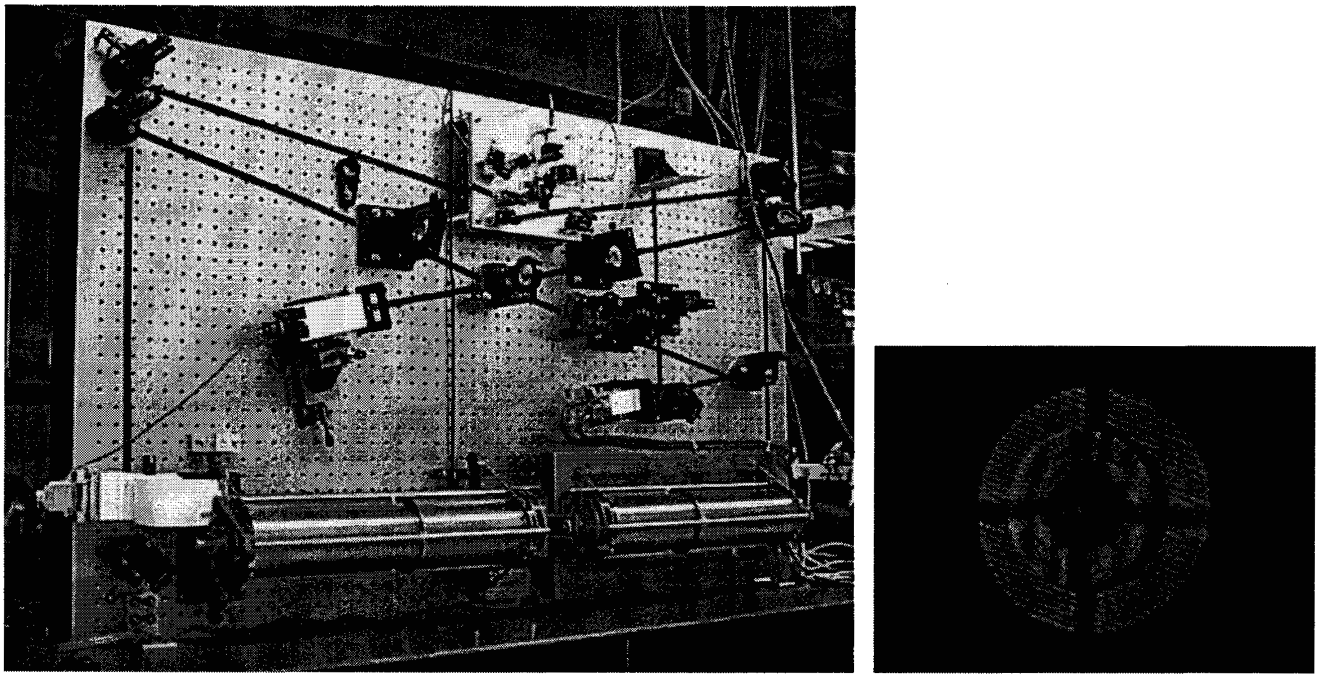


Figure 6a. & 6b. Left picture: beam combiner pallet (the delay lines are visible on the bottom) – Right picture: Starlight beam (10mm metrology obstruction , 10-20mm inner annulus fringes and 20-30mm outer annulus tilt guiding beam).

On the active delay line there are three stages of controlling the optical path length: stepper motor, voice coil and PZT stages. The stepper motor stage with a range of 2.5 cm and resolution of 2 μm translates the whole delay line. The voice coil with 3mm of range translates the optical tube on its 3.5 Hz resonance frequency flexures. Finally the PZT (called "servo PZT") with a range of 15 μm and 1 kHz bandwidth translates the secondary mirror. Another PZT with the range of only 1 μm (called "dither PZT") is stacked to the servo PZT and modulation of 250 Hz. The dither PZT is modulated by a 1 kHz triangular wave in order to track the fringe phase. Both the servo and the dither PZT are re-actuated. The internal metrology is used to servo the three stages of the delay line.

8. Detectors

The STB3 beam combiner layout is derived from the flight-article layout [3]. Two 30 arcminutes annular wedges are placed on each starlight beams before the main beam splitter in the combiner system. The inner part of the beam, not affected by the wedges, is used for fringe tracking. The outer part of the beam, deviated by the wedges, will form two separate spots when focused; it is used for star tracking. Figure 6b shows the recombined starlight beam. The beam combiner can simultaneously perform star tracking on a fast camera at 50 Hz, dithered fringe tracking on an avalanche photo-diode (APD) at 100 Hz and dispersed fringe tracking on a second camera ("science" beam combiner only).

Star tracking is done by focusing with a 750 mm lens the two recombined annular beams into a single camera developed at JPL. The guiding spots (36 μm in diameter) will be acquired at 500 frames per second on 24 μm square pixels. A resolution of one seventh of a pixel is required to obtain a 1 arcsecond star tracking.

The inner part of the recombined starlight beam is focused onto a multimode fiber connected an avalanche photodiode from EG&G. A counter stores the photon counts in four even bins (binning at 5 kHz). The phase of the fringe is calculated every millisecond using the value of the four bins. Dithered fringe tracking is achieved by comparing the phase of the fringes with the phase of the 1kHz dither PZT modulation wave. The internal laser metrology sensor monitors the dither wave. The phase error signal is sent to the delay line servo.

In the "science" beam combiner only, the inner starlight beam is dispersed by a 11.3° wedge onto a fast camera. The 550-850 nm spectrum is dispersed over 15 pixels on the camera and can be acquired at 1 kHz

9. Internal Metrology

The internal metrology is used to measure the relative changes in the pathlength between two arms of the interferometer. The measurement is used to command the active delay line' s motion to equalize the pathlength of the two arms. In STB3 there are three internal metrology systems, one for each interferometer. Metrology beam is 5 mm in diameter and goes through the center of the starlight beam. Figure XX shows the beam launcher in the beam combiner breadboard. The metrology beams are launched to the interferometer arms through a 6.25 mm hole at 37.5° angle in to two mirrors at the beam combiner. The metrology uses heterodyne method to measure relative changes in the pathlength.

As can be seen in the Figure 5, a small portion of the metrology beam in the beam combiner does not overlap with the starlight beam. In that segment, the metrology beam is parallel to the starlight beam but a few centimeters apart. The difference between the two paths should not have a significant effect on the measurement of relative pathlength changes.

4. METROLOGY

In any interferometer fringe position (X) is calculated by using the equation of $X = S \cdot B + C$, where S is a unit vector in the direction of the observing star, B is the baseline vector, and C is measuring the internal geometry of the interferometer. The internal metrology is capable of monitoring the changes in internal geometry of the interferometer (C). STB3 has three internal metrology systems, one for each interferometer. The baseline, B is measured by the external metrology.

10. Metrology Laser Beam Distribution

A distribution system was designed to support the large number of metrologies for STB3. Two 150 mW diode-pumped YAG infrared lasers at 1319 nm were selected for the metrology distribution. The main reason for this selection was the large numbers of metrologies (at least 32) and needs for a high power laser. The advantage of using IR is that the wavelength is outside of the visible starlight range, which remove the need for any filtering of metrology beam at the beam combiner. The disadvantage of using infrared laser is in difficulty working with invisible beam. To solve this problem, an Argon-Ion gas laser at 514nm has been selected to act as a beacon for the system. Figure 7 shows the design. There were two major reasons for selecting 514 nm laser as the beacon, a) this wavelength is outside of the starlight spectrum (532 nm and 550-700 nm) so there is no mixing with the starlight beams, b) eye sensitivity is good for this wavelength.

The reason for using two lasers relates to absolute distance measurement and will be explained later. Two 1x32 polarization maintaining wave-guide couplers will be used to distribute the laser beam to 32 beam launchers. The other two 1x16 polarization maintaining wave-guides are for the future addition of more metrologies. The visible light is coupled to the infrared beam through two 1x2 wave-guide couplers. The visible light is only coupled to the S polarization since its purpose is limited to alignment and safety. Since all the beam couplers are designed for 1319 nm, coupling 514 nm to them will cause the beams become multimode, which is not a concern. For the same reason the visible beams out of 1x32 and 1x16 beam couplers will have variation in intensities, but again that is not a concern as long as each channel has enough intensity to be visible. Initial tests with a 2x8 coupler at 532 nm indicate that enough light will be emitted on each channel.

11. Beam Launcher

The optical setup of a beam launcher for the internal metrology is shown in figure 8. A laser beam is split into two perpendicular polarizations (BL1); then the frequencies of the two polarizations are shifted by two known values. Next, the two polarizations are recombined and 10% of beam is sampled (BL3) to a detector as a "Reference" signal.

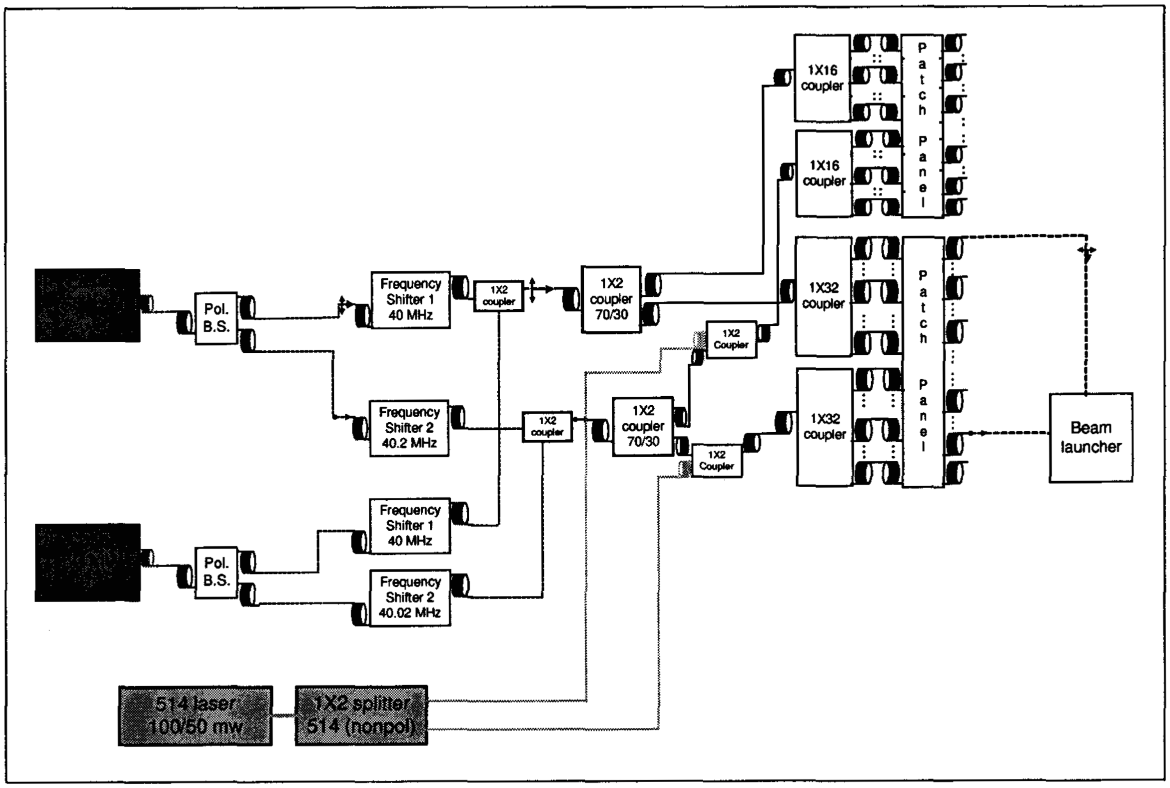


Figure 7. Metrology laser beam distribution.

The rest of the laser beam goes to a polarized beam splitter (BL4) which splits the beam to two perpendicular polarizations. Each polarization goes to one arm through a quarter wave plate and reflected back from a corner cube. The two polarizations then combined to a detector, after passing through a polarizer at 45°, as a "Unknown" signal. The phase difference between the "Unknown" and the "Reference" signals gives the change in the pathlength that is used to command the delay line. The internal metrology is mounted on a 240 x 200 x 12 mm Aluminum plate. The experimental results indicate 5-6 nm of error associated with each beam launcher.

12. External metrology

External metrology is used to measure the relative change and the absolute length of the baseline. The baseline is defined as a distance between the two vertexes of the corner cubes on the two siderostats. To measure the three baselines simultaneously and accurately, the metrology uses a boom and three corner cubes on the boom as shown in Figure 1a. Referencing the siderostats to the three corner cubes on the triangle allowed locating all the siderostats simultaneously and accurately. The details of the geometry explained in another paper.[6] The triangle is mechanically build such that there is no significant changes in the position of the corner cubes during measurement.

There are 18 external metrologies, three per siderostat. The external beam launchers have similar design as the internal beam launchers except only one polarization (S) goes to both corner cubes and the other polarization goes directly to the detector right after the beam splitter. External metrology makes two measurements, absolute distance measurement, and relative changes in the length. The absolute measurement of the distance will be explained below. Measurement of the relative change of the length is done by the same heterodyne technique used in the internal metrology.

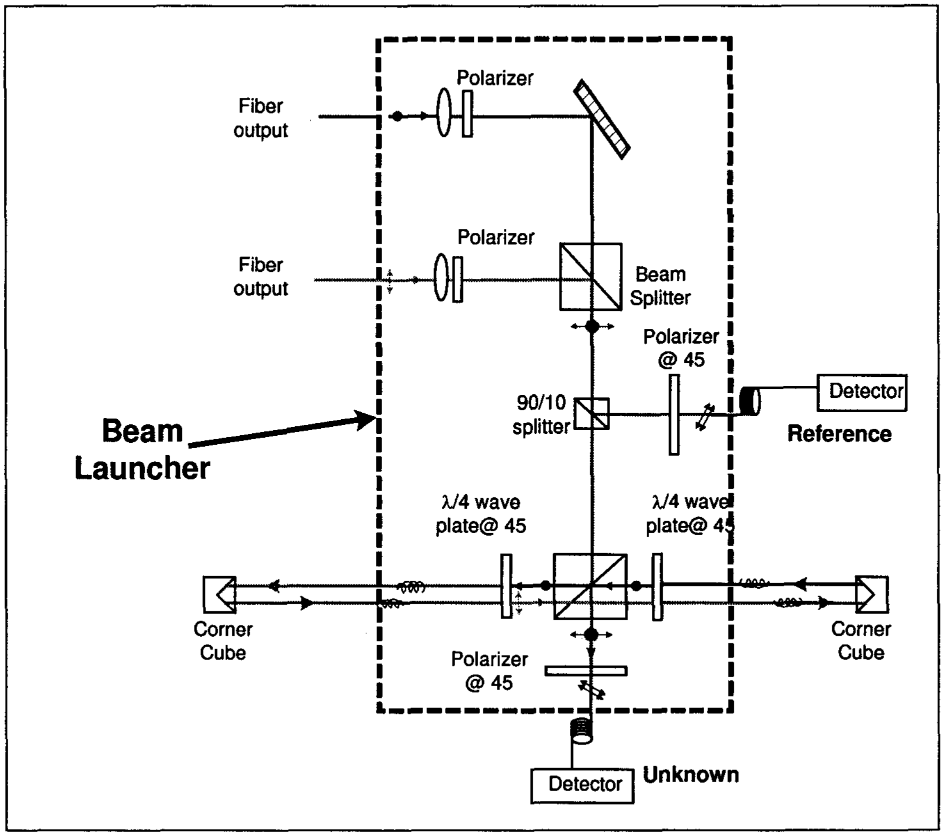


Figure 8. Internal metrology beam launcher.

13. Absolute Metrology

There are several methods for measuring absolute distance; STB3 uses the "frequency modulation" technique, first demonstrated by Yekta Gursel at JPL [7,8]. For a 6.5 meter long boom, a 2 meter wide triangle and a 10 bits phase-meter card, the accuracy of the measurement is about 30 mm. This technique uses two lasers, one being tuned and the other set at fixed frequency. The heterodyne frequency of one of the lasers is shifted by 200 kHz and the other one by 20 kHz. The reason for selection of these frequencies other than the limitation of the phase-meter card, is to have enough separation so there is no mixing of the signals at the detector. The technique works as follow: the frequency of one of the lasers is tuned to a known value (F) and the number of integer fringes is counted. The fractional fringes are measured by cyclic averaging in the beginning and the end of measurement (before and after tuning). In the mean time the second laser measures the relative changes in the length. The total numbers of fringes (N) is the sum of fringes from the first step, plus fractional fringes and correction from relative changes measurement. The absolute distance (D) then can be calculated by $D=CN/2F$, which C is the speed of light. The absolute distance will be used in pathlength feedforward equation to calculate fringes in the science baseline.

5. INITIAL PHASE

The development of the STB3 testbed will occur in two phases (called phase 1 and 2) in address the complexity of the problem in two steps. Phase 1 addresses the control system complexity and the pathlength feed-forward on a rigid table whereas phase 2 will address the extra complexity due to the flexible structure and the external metrology. The previous section was a description of Phase 2. Phase 1 is a simpler version of the STB3 phase 2 with the following differences:

- More rigid test-article: rigid table instead of the flight like structure.
- Smaller baseline: 4 meters instead of 8 meters.
- Common baseline (Son of SIM configuration) instead of multiple baselines (SIM classic configuration).
- Simpler pseudo-star layout: only 4 gratings are necessary to feed a common baseline (instead of 8 gratings).

- Single pseudo star metrology at any time: by adding or removing a corner cube we were able to select the path to monitor.
- Only one corner cube on a spider mount supporting all three internal baselines (Son of SIM configuration) instead of corner cubes in each siderostat.
- 1-D only external metrology monitoring changes in the baseline instead of the 3-D external metrology.
- No metrology boom.
- No absolute metrology is needed.
- Visible metrology: HeNe laser at 633 nm instead of infrared 1319 nm.

Initial setup assembled, optical results, metrology test, DL jitter and, FT jitter and band, star tracker, multiple baseline operation.

Figure 9a shows a picture of the phase 1 testbed with the pseudo-star table in the back and the test-article on the front. Two beam combiners are visible while the last one is on the back on the second one. All the optics, sensors and actuators are installed and aligned. One baseline is fully operational: internal path stabilization by the active delay line and fringe tracking using the APD. The two others baselines are still under test prior to run the three baselines simultaneously.

Test setup and some results from pseudo star metrology are shown on the figure 9b. More results are presented in reference [5].

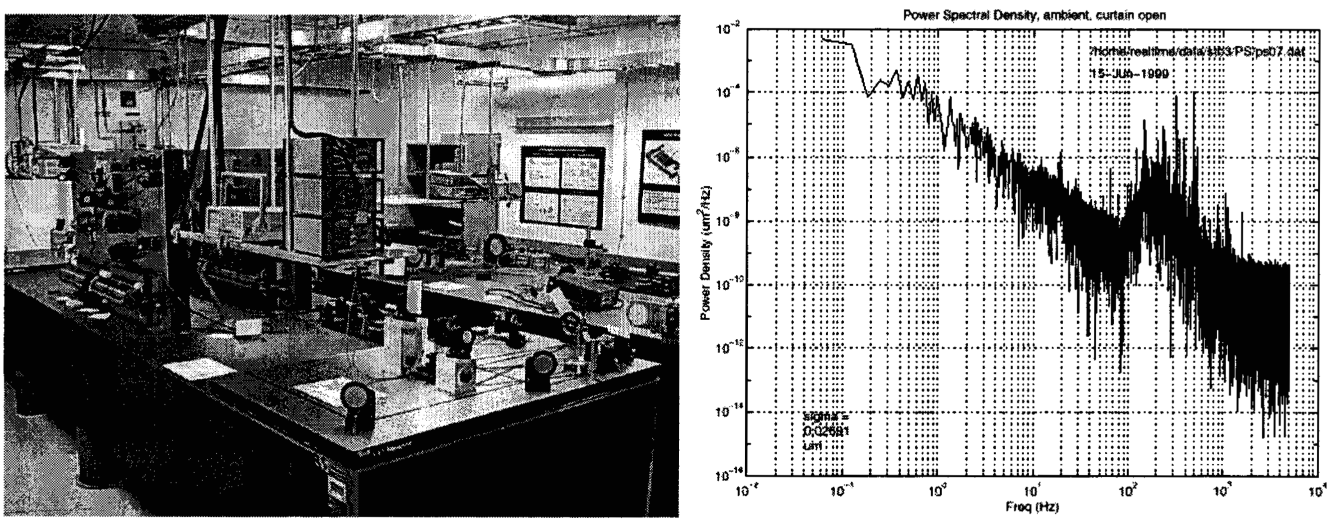


Figure 9a. & 9b. Left picture: STB3 initial phase setup (the test-article is nearest table, the two beam combiner pallets are visible in the left side of the picture and the pseudo-star table on the back of the picture). Right picture: power spectrum density of the pseudo-star optical path jitter (from the parabola to the grating, 26 nm rms from 0.1 Hz to 5 kHz).

6. CONCLUSION

In this paper, we have presented the SIM system testbed III optical design: the triple reverse interferometer pseudo-star, the SIM-like test-article. We also mentioned the phasing of the testbed development. The phase 1 (simplified version) testbed is fully built and partially running. The full functionality of the phase 1 testbed will be completed by the summer 2000. The design of the phase 2 (full complexity) testbed is completed. The phase 2 will be built in the summer 2000, starting by the structure and the external metrology boom, in order to produce performance results in 2001. The results are indispensable for the Interferometry Technology Program in order to predicate SIM performances.

7. ACKNOWLEDGEMENTS

The research described was performed at the Jet Propulsion Laboratory of the California Institute of Technology, under contract with the National Aeronautics and Space Administration. The authors thank the leaders of the Interferometer Technology Program, Bob Laskin, Jeffrey Yu, and Ben Parvin for their technical and financial support.

8. BIBLIOGRAPHY

1 1. P. C. Irwin and R. Goullioud, "Hardware design and object-oriented hardware driver design for the Real-time Interferometer Control System Testbed", *Proc. of SPIE conference on astronomical Interferometry*, vol. 3350, pp. 146-152, 1998.

4 2. R. J. Calvet, D. M. Moore, R. L. Grogan and G. H. Blackwood, "Enabling design concepts for a flight-qualifiable optical delay line", *Proc. of SPIE conference on astronomical Interferometry*, vol. 3350, pp. 35-47, 1998.

5 3. R. P. Korechoff, S. B. Shaklan, Y. Rin, R. D. Bartos and D. M. Moore, "Design and performance of an astrometric beam combiner for space interferometry", *Proc. of SPIE conference on astronomical Interferometry*, vol. 3350, pp. 26-34, 1998.

2 4. B. E. Hines, "SIM System Testbed III", *Proc. of SPIE conference on Interferometry in Optical Astronomy*, vol. 4006, 2000.

9 5. B. Nemati, "Demonstration of pathlength feed-forward for precision dim-star astrometry", *Proc. of SPIE conference on Interferometry in Optical Astronomy*, vol. 4006, 2000.

6 6. B. E. Hines, "Optical Trust & Retroreflector Modeling for Picometer Laser Metrology", *SPIE*, 199XX …

7 7. Y. Gursel, "Metrology for spatial interferometry II", *Proc. of SPIE conference on Spaceborne Interferometry II*, Vol. 2477, pp. 240-258, 1995.

8 8. Y. Gursel, "Metrology for spatial interferometry III", *Proc. of SPIE conference on Space Telescopes and Instruments IV*, vol. 2807, pp. 148-161, 1996.

3 9. A. Azizi, "Architecture for Pseudo Star Metrology", *JPL Internal Memo*, 1999.

10. Previous MPI paper.